PARTS OF THE ORIGINAL DOCUMENT

ARE OF POOR REPRODUCTIVE QUALITY

CERTAINES PARTIES DU DOCUMENT ORIGINAL

SONT DE PIÈTRE QUALITÉ DE REPRODUCTION

CONTRACT SERIAL NO. OST84-00512
REQUISITION NO. 23440-5-9015
CONTRACTOR: QUEEN'S UNIVERSITY

PILOT SCALE TRIALS ON ATMOSPHERIC FLUIDIZED BED COMBUSTION OF A BRITISH COLUMBIAN ANTHRACITE (MT. KLAPPAN)

H.A. Becker, R.K. Code and J.R. Stephenson
Department of Chemical Engineering
Queen's University at Kingston
Kingston, Canada K7L 3N6

A report to
Energy Mines and Resources Canada
Energy Research Laboratories, CANMET
Ottawa, Canada

Technical Report QFBC.TR.87.4
Queen's Fluidized Bed Combustion Laboratory.

37 Ap

MICROMEDIA

PREFACE

This is one of six reports on work performed under a contract with Supply and Services Canada (DSS) under the auspices of the Canada Center for Mineral and Energy Technology (CANMET), Energy, Mines and Resources Canada:

DSS Contract Serial No. : OST84-00512

Title: A Program of Pilot Scale R&D on Bubbling-Bed Atmospheric Fluidized Bed Combustion

Principal Investigators: Dr. H.A. Becker and Dr. R.K. Code,
Department of Chemical Engineering,
Queen's University,
Kingston, Ontario K7L 3N6
Telephone: (613) 545-2767

Scientific Authority: Dr. E.J. Anthony, Building 1,
Energy Research Laboratories, CANMET,
Haanel Drive, Bells Corners, Ontario

Postal address:
Energy Research Laboratories, CANMET,
555 Booth Street,
Ottawa, Ontario K1A 0G1
Telephone: (613) 996-4570, ext. 185

Commencement date: April 1, 1985

Delivery date: March 31, 1987

Consignee: Energy, Mines and Resources, Energy Research Laboratories, CANMET, 555 Booth Street, Ottawa, Ontario K1A 0G1

Science Procurement Manager: Ms. J.P.S. Sztramko, Science Branch
Supply and Services Canada, Place du Portage,
Phase III, 11 Laurier Street, Hull, Quebec
K1A 0D5

CONTENTS

NOTATION iii

1. INTRODUCTION 1

2. THE PILOT PLANT 2

3. MATERIALS 4

4. OPERATING CONDITIONS 4

5. THE CARBON BALANCE 11

5.1 Carbon content of product solids 11
5.2 Ratios of carbon fluxes 13
5.3 Carbon burn-up efficiency 15
5.4 Carbon balance check 15

6. THE SULPHUR BALANCE 18

6.1 Closures on the sulphur balance 18
6.2 Sulphur content of product solids 18
6.3 Ratios of sulphur fluxes 22

7. THE NITROGEN BALANCE 25

7.1 NO_x levels in stack gas 25

7.2 Conversion of fuel N to NO_x 25

8. COMPARISON WITH HIGHVALE COAL 28

8.1 Carbon burn-up efficiencies 28

9. CONCLUSION 30

NOTATION

Subscripts (codes for material streams)

a	combustion air
b	bed product (material removed directly from the bed)
c	cyclone product (cyclone catch not recycled)
d	cycloned solids (dust catch in cyclone)
e	elutriated solids (cycloned solids d plus baghouse product h)
f	fuel (here coal)
g	stack gas
h	baghouse product
o	overhead product solids (cyclone product c plus baghouse product h)
p	total product solids
r	recycled cycloned solids
s	sorbent or bed material (here sand)

Variables

COT	continuous-mode operating time, h
D_p	particle diameter, mm. Here determined by sieve analysis
$\hat{D}_p$	characteristic diameter for particles of mixed size, mm: defined by $\hat{D}_p = D_p$ at $F_D = 1/2$
F_D	distribution function, $F_D = F_D(D_p)$, of particle size in a population: the mass fraction of particles smaller than the argument value of D_p
m	mass of material, kg
m_b	bed mass (holdup), kg
$\dot{m}$	mass flux, kg/h

n_t number of in-bed cooling tubes

T_b bed temperature, K

v superficial gas velocity up combustor, m/s, also called the fluidizing velocity; measured at the bed temperature, freeboard pressure, and exit gas compositions

$W_{i,m}$ mass ratio of component i in the m'th material stream, here the mass fraction d.b. (dry basis), i.e., the mass fraction of i per unit mass of dry matter

ε_a excess air level, $(\dot{n}_a/\dot{n}_{a,st}) - 1$, where $\dot{n}_{a,st}$ is the theoretical air requirement for complete combustion, also expressed as a percentage

τ_b $= m_b/\dot{m}_b$, estimate of residence time of bed product in combustor, h

τ_p $= m_b/\dot{m}_p$, mean residence time of particles in combustor, h

ϕ_a air equivalence ratio: $1 + \varepsilon_a$

$\phi_{i,mn}$ mass flux ratio of component i in the m'th and n'th material streams

1. Introduction

This report examines the atmospheric fluidized bed combustion (AFBC) of an anthracite from the Mt. Klappan region of British Columbia. The work is part of a continuing series of investigations on the combustion of candidate fuels for AFBC. Earlier reports (Becker and Code, 1983; Becker et al, 1985) examined the combustion of three Eastern Canadian coals (Minto, Devco, Evans), an Appalachian coal (Kentucky No. 9), and Syncrude coke.

Carbon, sulphur and nitrogen balances are carried out on the combustor and the results are summarized in terms of the ratio of the fluxes of a particular component in the process streams of interest. This is a convenient format for examining the extent of carbon combustion and the fate of other constituents in the fuel. As examples, the fraction of the fuel carbon which remains unburnt and the distribution of unburnt carbon among the three streams of product solids may be examined. Particular attention is focussed on the combustion efficiency as measured by carbon burn-up, the capture of fuel sulphur by the streams of product solids and the conversion of fuel nitrogen to NO_x.

2. The pilot plant

The AFBC pilot plant at Queen's University is described in detail in an earlier technical report (Becker and Code, 1982). Several minor modifications completed after the issuance of this first report are described by Becker et al, 1985. A simplified flowsheet of the plant is shown in Fig. 2.1.

The cross-section of the combustion chamber is nearly square, 381 mm by 406 mm, with a cross-sectional area of 0.155 m^2. Combustion air is dispersed through a distributor plate fitted with 100 dispersion heads uniformly spaced on a rectangular pitch. The temperature of the bed is controlled by the adjustment of the flow of cooling water through in-bed cooling tubes constructed from 0.5-in standard steel pipe. Up to 48 tubes in a variety of configurations may be inserted through a matrix of ports in refactory-lined and water-jacketed panels on opposite walls of the combustion chamber. The overall height of the unit from the distributor plate to the top of the freeboard is 4 m.

The combustor has provision for overbed and underbed feeding and bed solids may be removed by overflow or by underbed extraction. The bulk of the elutriated solids are removed by a cyclone separator. A flow splitter and pneumatic injection system allows an adjustable fraction of the product solids from

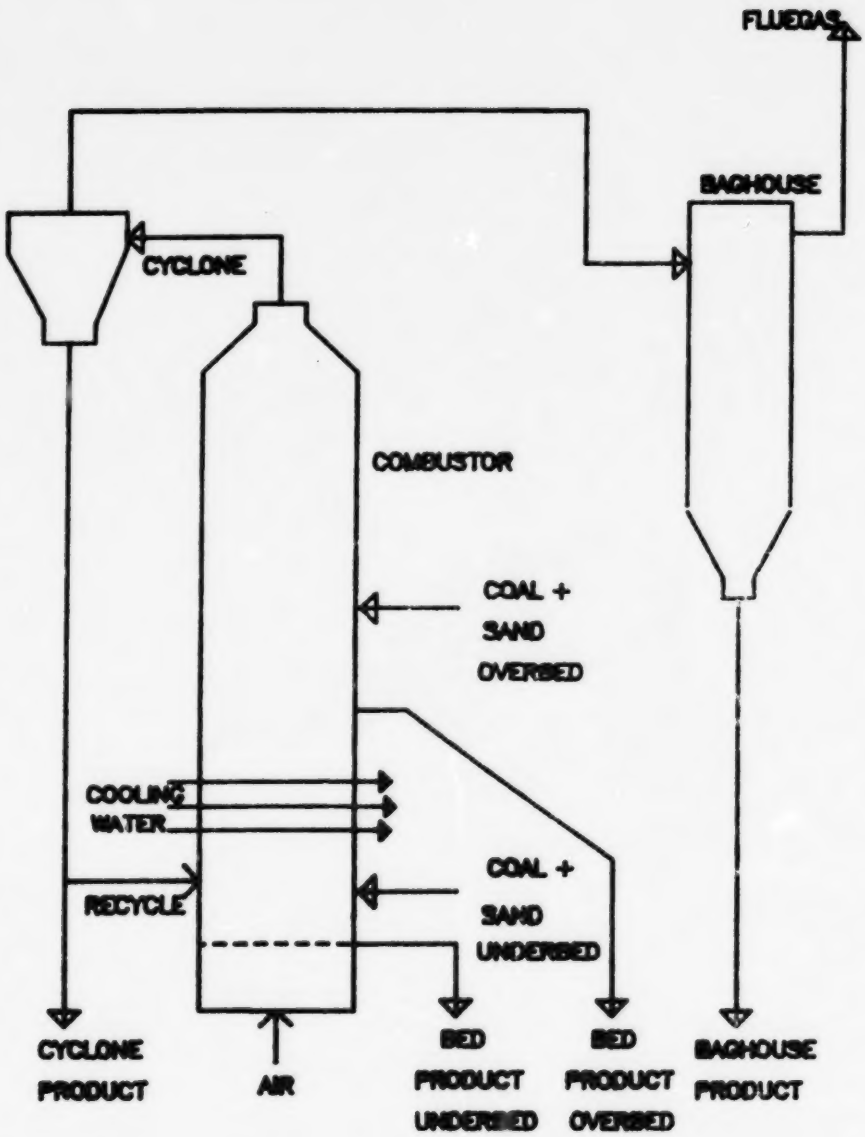


Fig. 2.1 Flowsheet of the AFBC pilot plant

the cyclone to be recycled to the combustor. Additional fines are recovered from the exhaust gases in a baghouse.

3. Materials

The Mt. Klappan anthracite was supplied by Gulf Canada Ltd. Two lots were used in the trials: a run-of-mine fraction crushed to minus 0.5-in and a washed fraction. Particle size distributions determined by sieve analysis of samples from the two lots are illustrated in Fig. 3.1. Characteristic particle diameters, $\hat{D}_p$, are: 2.5 mm for the unwashed lot and 1.8 mm for the washed lot. Proximate-ultimate analyses and ash analyses for the two lots of Mt. Klappan coal are summarized in Table 3.1 and Table 3.2. Ash fusion temperatures under reducing and oxidizing conditions are given in Table 3.3.

The sand, nearly pure silica, which was used as a bed material was obtained from a local Kingston supplier. It is double screened for use in sand-blasting operations. The particle size distribution of the sand is illustrated in Fig. 3.2. The characteristic particle diameter, $\hat{D}_p$, is 0.6 mm.

4. Operating conditions

Operating conditions for the trials with Mt. Klappan anthracite are summarized in Table 4.1. The combustor was operated in the underbed feed mode and bed holdup was controlled

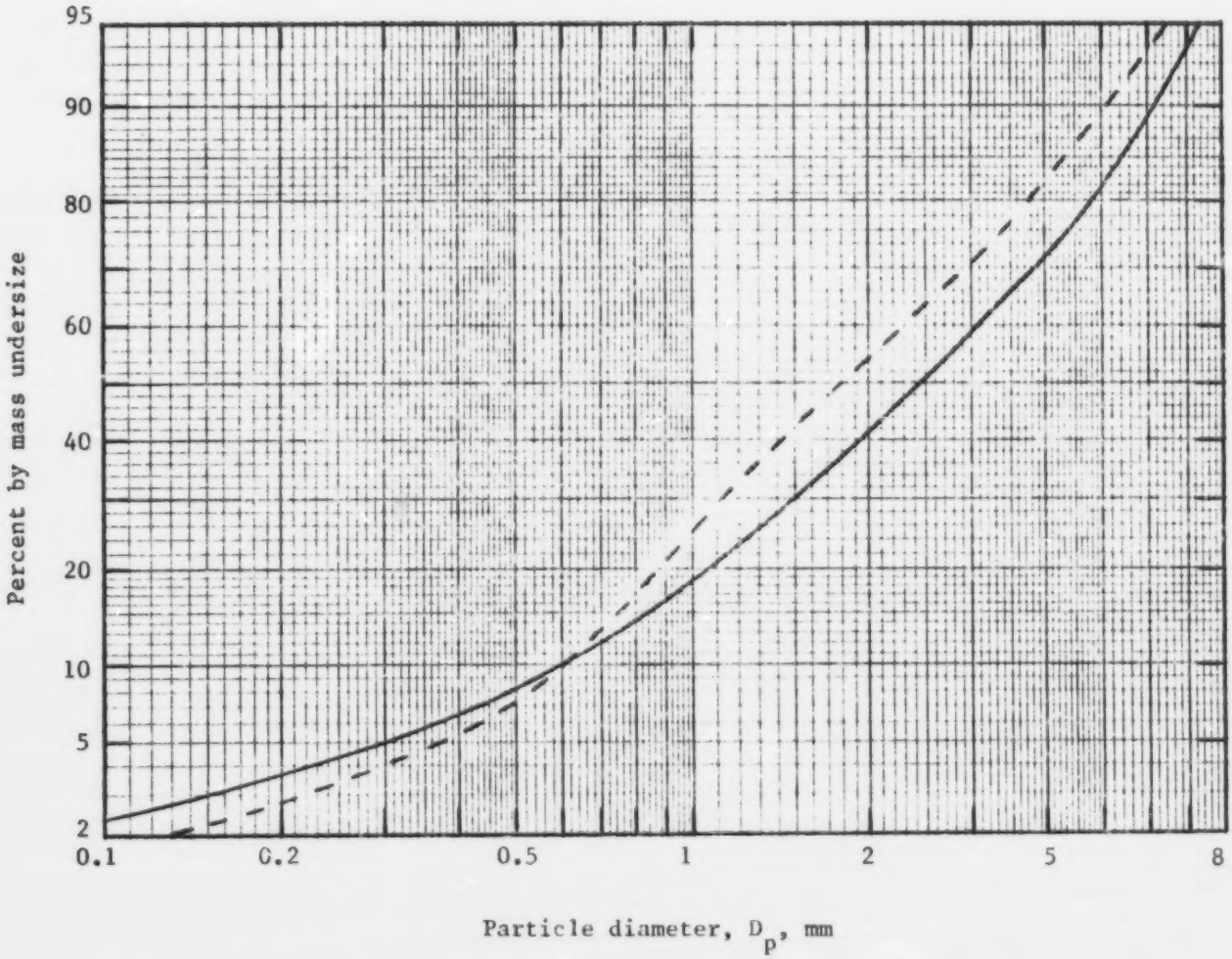


Fig. 3.1 Particle size distributions of Mt. Klappan coal.

_____ unwashed lot, $\hat{D}_p$ = 2.5 mm

-------- washed lot, $\hat{D}_p$ = 1.8 mm

Table 3.1 Chemical analysis of run of mine Mt. Klappan coal, nominal size -1/2 inch.

Proximate/Ultimate Analysis

	(weight %, dry basis)		
	a	b	c
REPORTER	QAFBC	ERL	Gulf
MOIS	12.62	2.43	2.3
ASH	27.36	21.58	20.2
VCM	6.46	9.05	6.8
FC	66.18	69.37	73.0
C	65.72	69.41	73.91
H	2.11	2.12	1.75
N	0.89	0.95	0.34
S	0.63	0.39	0.47
O	3.44	7.84	3.33
HHV. (MJ/kg)	33.44 (MAF)		33.55 (MAF)

Ash Analysis

	(weight %, ignited basis)		
	a	b	c
REPORTER	QAFBC	ERL	Gulf
SiO2		67.96	60.90
Al2O3		19.76	22.85
Fe2O3		3.75	6.45
TiO2		1.39	1.13
CaO		1.05	1.58
MgO		1.38	2.27
Na2O		1.32	1.57
K2O		1.17	1.45
BaO		0.24	
SrO		0.07	
SO3	1.32	0.18	0.95
Mn3O4		0.00	
P2O4			

a Present lot of coal, average analyses of 4 samples.

b Anthony (1985), analysis of single sample by ERL.

c Anthony (1985), analysis of single sample by Gulf.

Table 3.2 Chemical analysis of washed Mt. Klappan coal, nominal size -1/2 inch.

Proximate/Ultimate Analysis

(weight %, dry basis)

REPORTER	QAFBC[a]
MOIS	9.95
ASH	8.72
VCM	6.98
FC	84.30
C	86.24
H	2.54
N	1.09
S	0.67
O	0.80
HHV. (MJ/kg)	33.44 (MAF)

Ash Analysis

(weight %, ignited basis)

REPORTER	QAFBC[a]
SO3	1.7

[a] Present lot of coal, average analyses of 5 samples.

Table 3.3 Ash fusion temperatures of fuels.

FUEL	Klappan (raw)	Klappan (raw)	Klappan (washed)	Klappan (washed)
REPORTER	COM [a]	COM [a]	COM [a]	COM [a]
CONDITIONS	Reducing	Oxidizing	Reducing	Oxidizing
I.D., C	1239	1335	1303	1384
S.S., C	1298	1349	1352	1432
S.H., C	1347	1427	1395	1454
F., C	1438	1443	+1454	+1454

I.D. = Initial Deformation Temperature
S.S. = Spherical Softening Temperature
S.H. = Hemispherical Softening Temperature
F. = Fluid Temperature

[a] Analysis by commercial analyst on single sample from present lot.

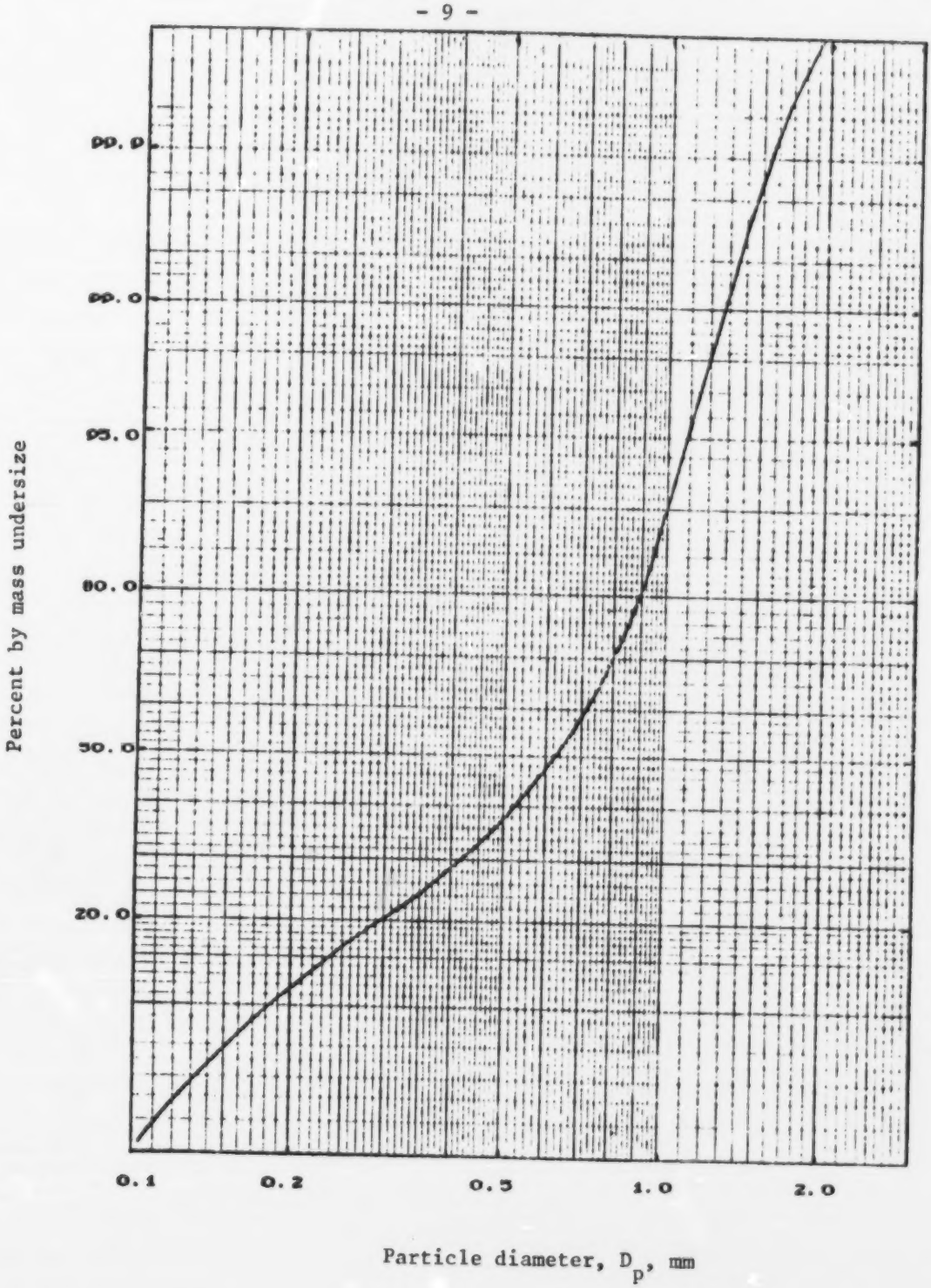


Fig. 3.2 Particle size distribution of Kingston sand

Table 4.1 Operating Conditions

Trial	n_t	Coal		Sand		Air		r	T_b,	v,	COT,	Bed Height,
		$\hat{D}_p$, mm	$\dot{m}_f$, kg/h	$\hat{D}_p$, mm	$\dot{m}_s$, kg/h	$\dot{m}_a$, kg/h	ε_a, %		°C	m/s	h	cm
		washed										
860113	12	1.81	40.8	0.6	6.6	382	- 4.5	0.0	936	2.3	6.9	35
860122	4	1.81	20.9	0.6	5.8	183	-11.0	0.93	933	1.1	12.2	35
860127	4	1.81	21.9	0.6	4.2	235	9.8	0.0	896	1.4	9.2	33
		unwashed										
860114	12	2.48	60.0	0.6	6.0	408	- 5.7	0.0	933	2.5	11.0	45
860120	8	2.48	45.5	0.6	6.6	324	- 1.4	0.56	936	2.0	10.0	37
860121	8	2.48	41.5	0.6	5.1	286	- 4.5	0.0	924	1.7	5.4	46

by the overflow of bed solids. The height of the expanded bed ranged from 35 cm to 48 cm. These estimates of bed height are based on the measurement of the pressure distribution along the wall of the combustor. Bed temperatures, 895 °C to 936 °C, are in the upper temperature range for the operation of fluidized bed combustors. The superficial fluidizing velocity ranged from 1.1 m/s to 2.5 m/s. The lower limit is well above the minimum fluidizing velocity for the bed solids.

The oxygen concentration in the stack gas is monitored and used as a convenient qualitative indicator of the effectiveness of the operation of the combustor. Normally, oxygen concentrations in the observed range, 2.4 to 5.8 mol % O_2, would indicate an excess of oxygen in the air feed. However, in the trials with the refractory Mt. Klappan anthracite only the trial (860127) corresponding to the upper limit of oxygen concentration had a positive excess air feed. Running times in the continuous operating mode (COT) ranged from 5.4 to 12.2 hours. Feeding difficulties with the wet coal feed reduced the COT below the target of 12 hours in a number of the runs.

5. The carbon balance

5.1 Carbon content of product solids

Fig. 5.1 shows the carbon content of the streams of product solids from the bed, cyclone and baghouse. The ranges of

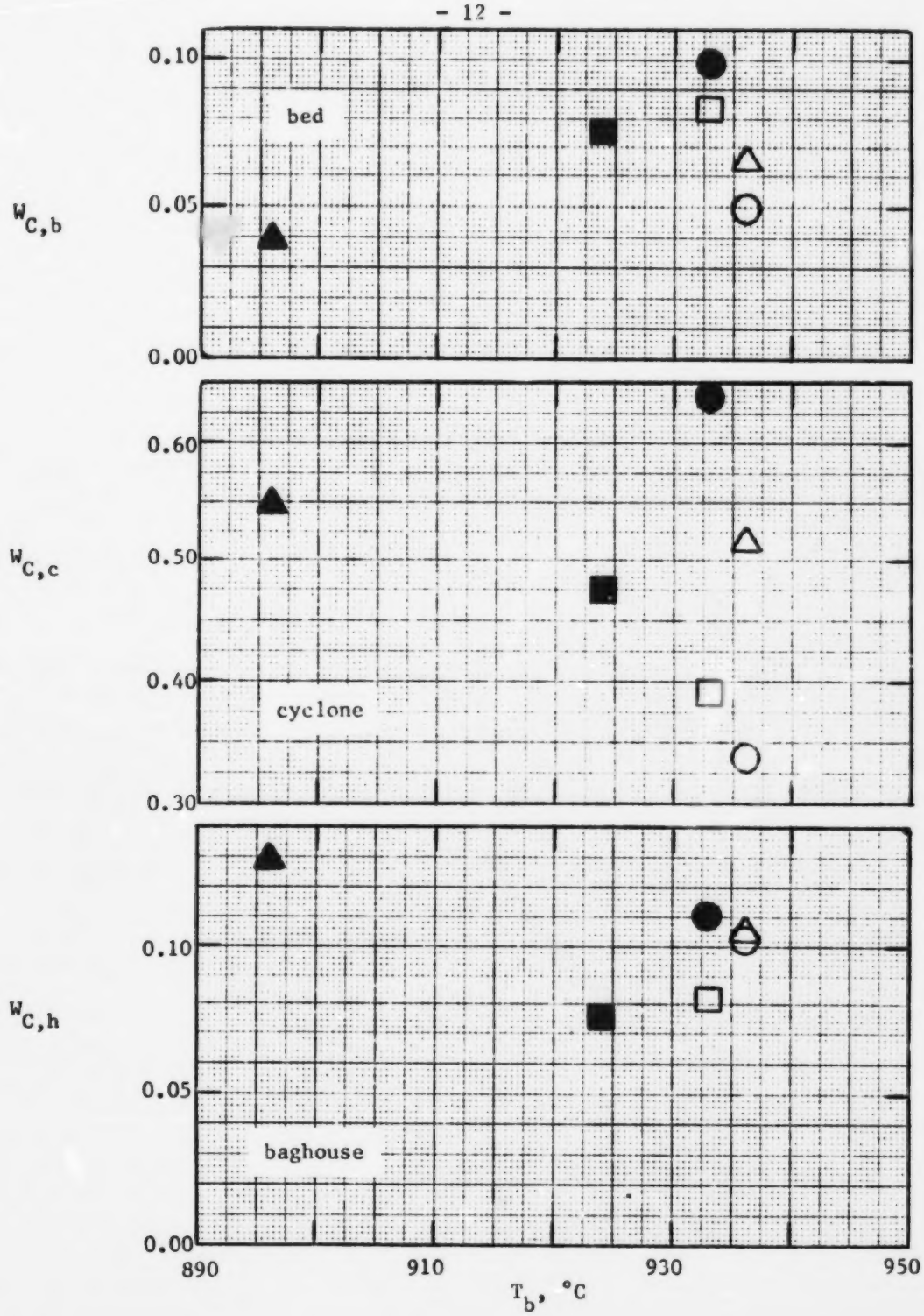


Fig. 5.1 Mass fraction carbon in streams of product solids.

Key to symbols:

	v,m/s	r	coal		v,m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

carbon content are: 3.9---9.9 % for the bed solids, 33.8---64.1% for the cyclone solids, and 7.5---12.9 % for the baghouse solids. The ranges of carbon content for the bed solids and cyclone solids are significantly higher than the ranges observed in the earlier work on more reactive coals (Becker et al, 1985). The recycle of cyclone solids increases the carbon content of the product solids but, as will be seen later, the overall effect is to increase the carbon burn-up and hence the combustion efficiency.

5.2 Ratios of carbon fluxes

The ratio of the carbon flux in individual product streams to the carbon flux in the feed is a convenient format for examining the fate of the carbon in the fuel. Flux ratios for the three streams of product solids are plotted in Fig. 5.2. The stream of cyclone solids is the predominant carrier of unburnt carbon; 4.3---19.4 % of the carbon in the fuel leaves in the cyclone solids while only 0.7---3.2 % and 0.1---0.5 % leave, respectively, in the bed solids and the baghouse solids. The lowest value of 4.3 % for the cyclone solids corresponds to a recycle fraction of 0.93. The values for bed temperatures of 933 °C and 936 °C and zero recycle fraction are 19.4 % and 17.8 %. The recycle of cyclone solids increases the fraction of the fuel carbon leaving in the baghouse solids but this effect is not significant since only a small fraction of the carbon in the fuel leaves as unburnt carbon in the baghouse solids. At a bed

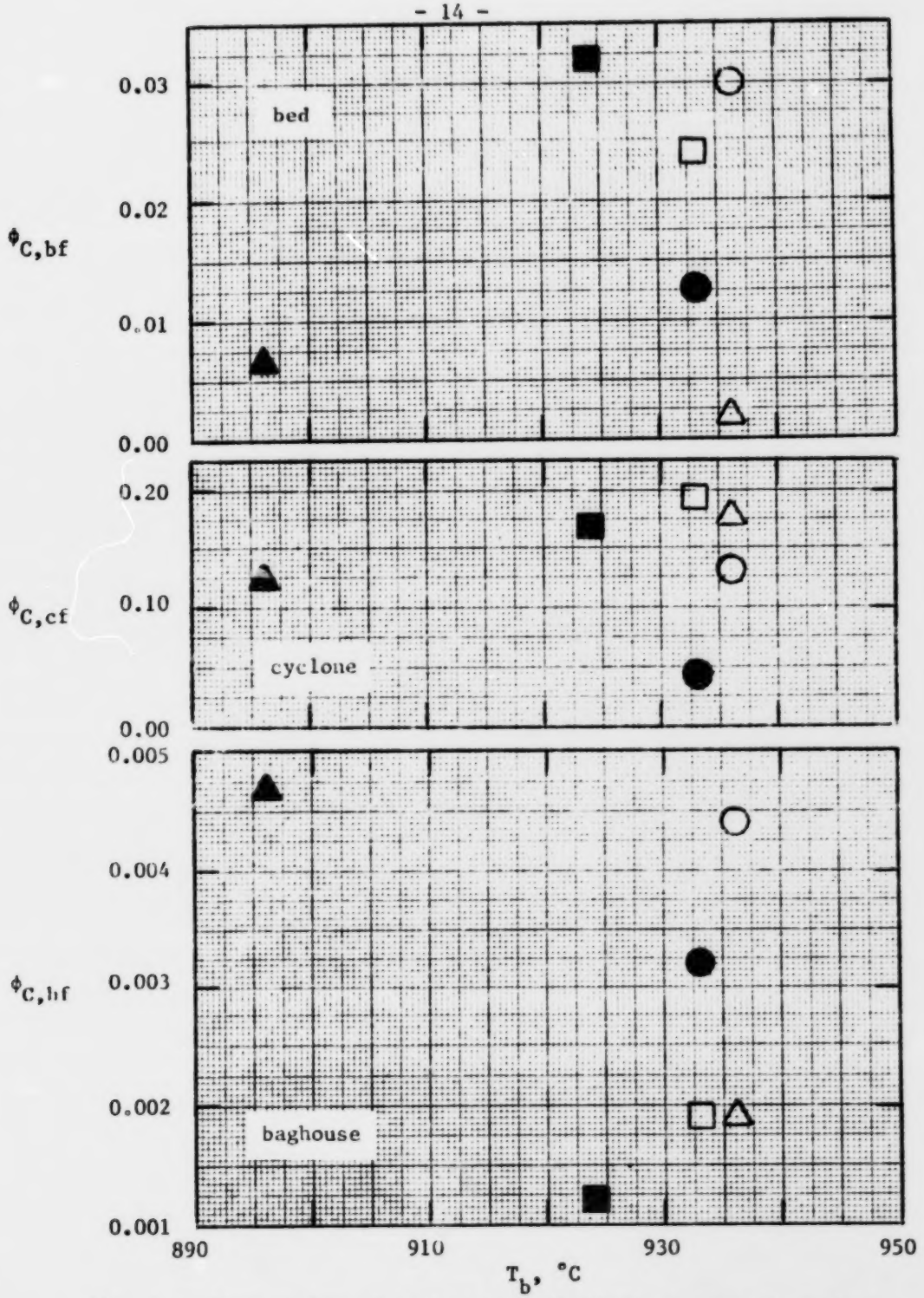


Fig. 5.2 Flux ratios of carbon in individual streams of product solids to carbon fed in fuel.
Key to symbols:

	v,m/s	r	coal		v,m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

temperature of 933 °C, the overhead carbon loss (the sum of the residual carbon in the cyclone and baghouse streams) is reduced from 19.6 % to 4.6 % of the fuel carbon as the recycle fraction is increased from 0.0 to 0.93. The distribution of unburnt carbon among the three streams of product solids is examined in Fig. 5.3. Again, the pronounced effect of the recycle of cyclone solids is evident.

5.3 Carbon burn-up efficiency

In this analysis the carbon burn-up efficiency is used as a measure of the combustion efficiency. This is a reasonable approximation for fuels with a high ratio of carbon to other combustibles. The burn-up efficiencies, Fig. 5.4, range from 78.0 % to 94.2 %. At the highest excess air level (9.8 %) and zero recycle fraction, the burn-up efficiency is 86.6 %. The highest burn-up efficiency (94.2 %) was achieved at the lowest excess air level (-11.0 %) but with a recycle fraction of 0.93. Mt. Klappan coal is a refactory fuel and recycle of overhead fines is required to achieve an acceptable level of combustion efficiency.

5.4 Carbon balance check

Closures on the carbon balances fall within an acceptable range. The carbon accounted for in the product streams is plotted versus the carbon entering in the feed in Fig. 5.5. With

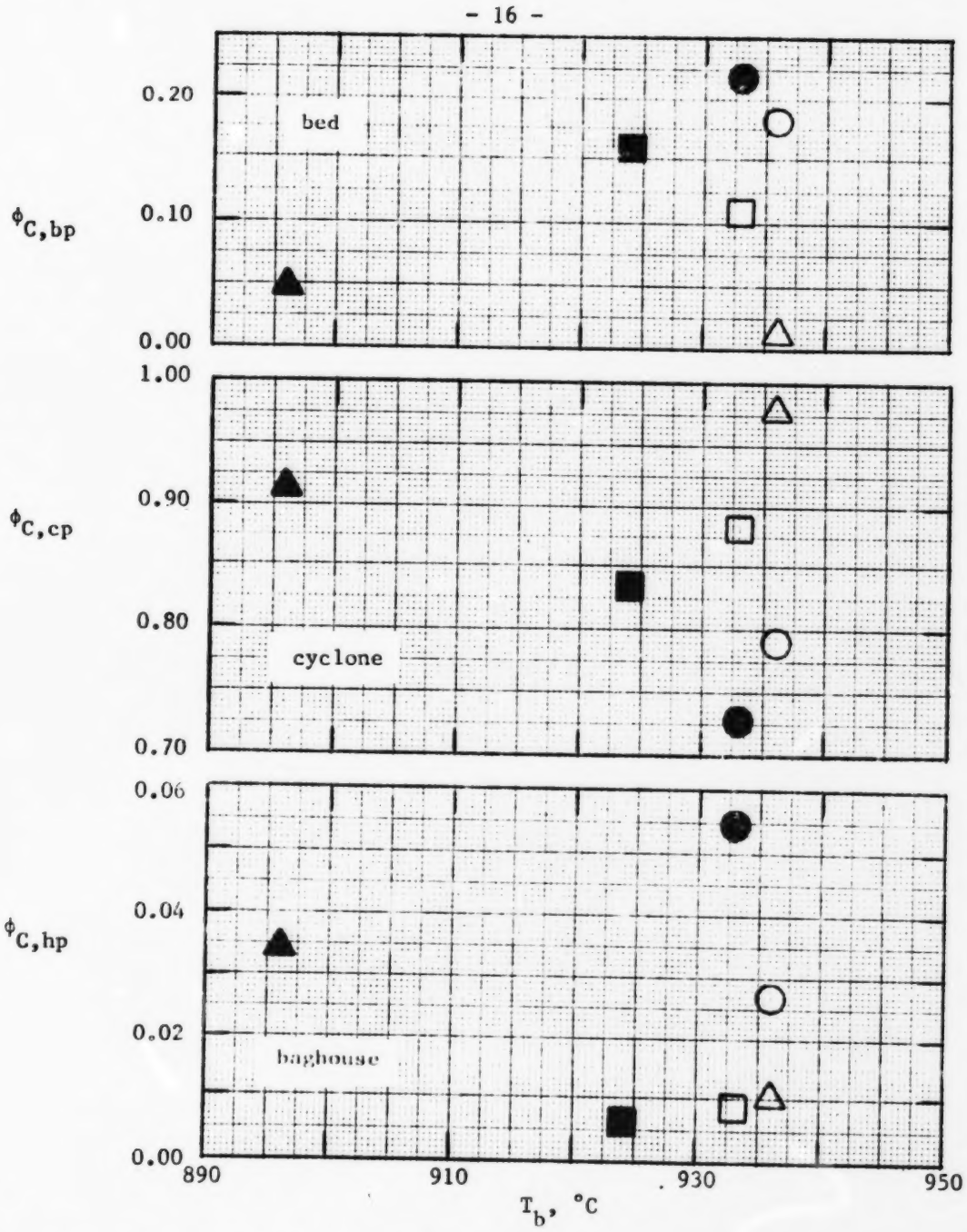


Fig. 5.3 Distribution of carbon among streams of product solids - ratio of carbon in an individual stream to total carbon loss in product solids.

Key to symbols:

	v,m/s	r	coal		v,m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

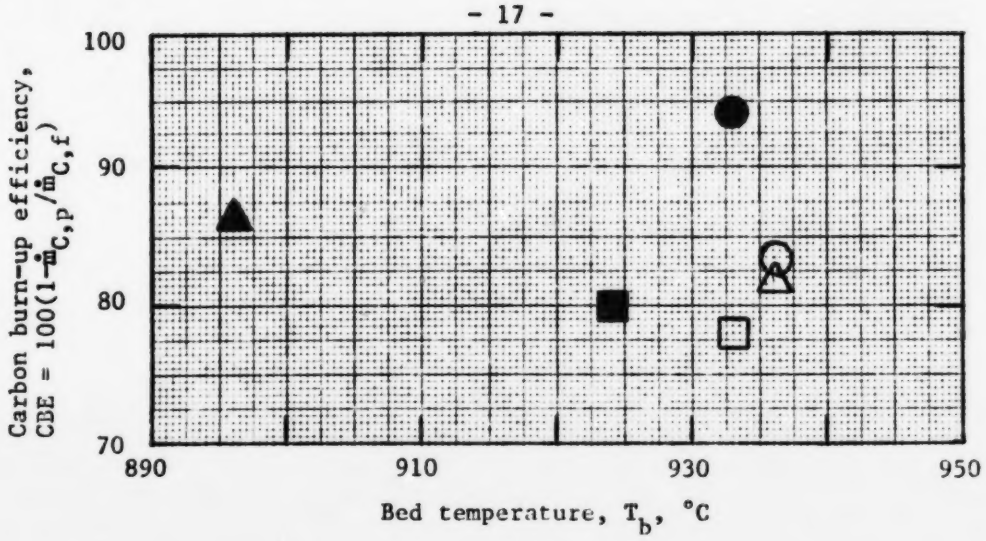


Fig. 5.4 Carbon burn-up efficiencies. A key to the symbols accompanies Fig. 5.3.

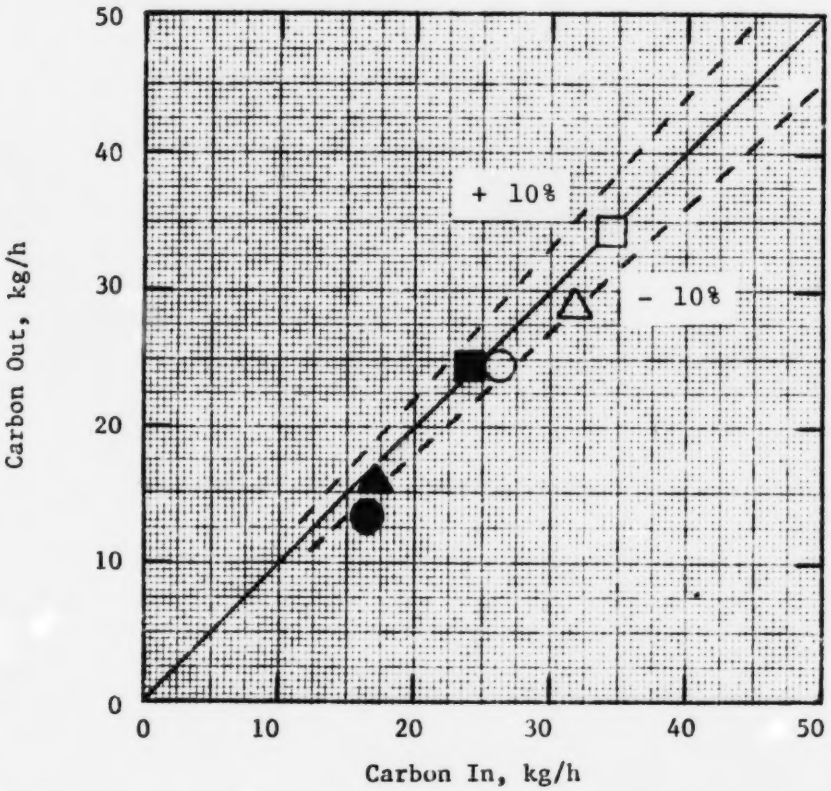


Fig. 5.5 Carbon balance check. A key to the symbols accompanies Fig. 5.3.

the exception of Trial 860122, the carbon balances fall within the ± 10 % boundaries in Fig. 5.5.

6. The sulphur balance

6.1 Closures on the sulphur balances

Closures on the sulphur balances are unsatisfactory. Fig. 6.1 illustrates the lack of agreement between estimates of residual sulphur in the product solids based on the flowrates and analyses of the stack gas with estimates based on the flowrates and analyses of the product solids. With the exception of Trial 860120, the estimates of residual sulphur based on the stack gas are consistently much higher than the estimates based on the product solids.

6.2 Sulphur content of product solids

With the preceding reservations, the mass fractions sulphur in the three streams of product solids are presented in Fig. 6.2 and Fig. 6.3. The sulphur content of the bed solids is in the range 0.15---0.31 % while the sulphur content of the baghouse solids is approximately ten times that of the bed solids, 2---3 %. The sulphur content of the cyclone solids is in the range 0.5---0.7 %. In Fig. 6.3 the mass fractions sulphur are plotted versus the carbon content. There is no apparent effect of carbon content on the levels of residual sulphur in the

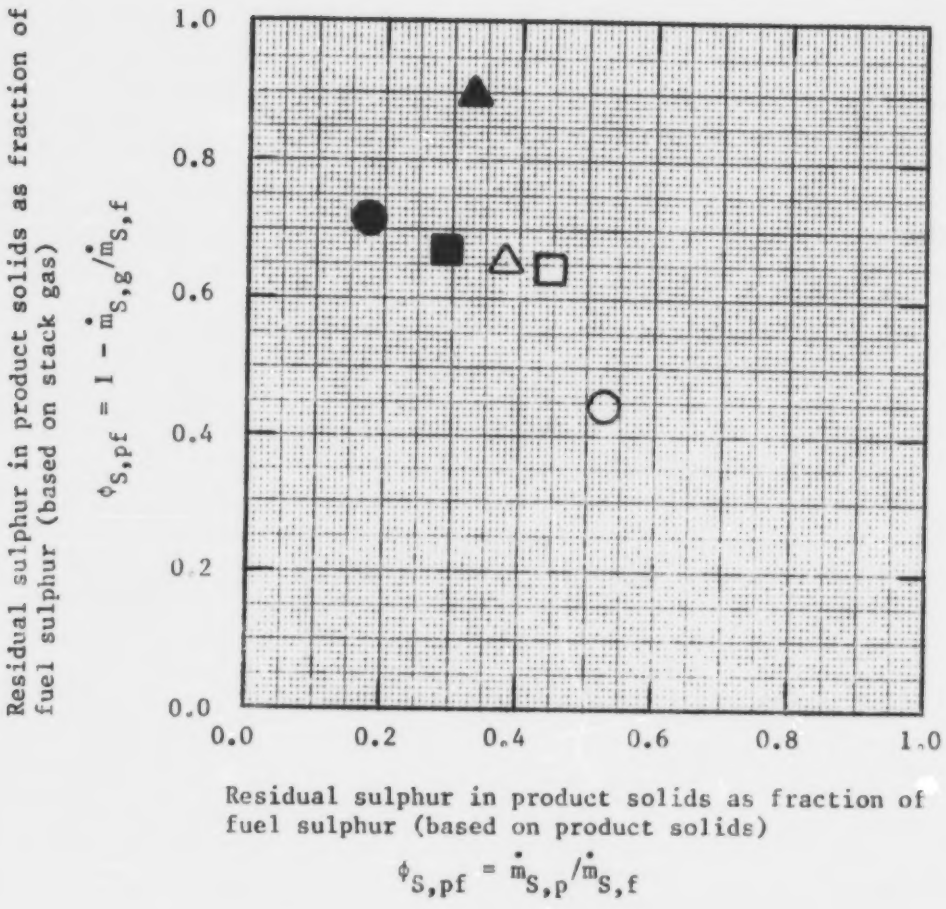


Fig. 6.1 Comparison of estimates of residual sulphur based on flowrates and analyses of stack gas with estimates based on flowrates and analyses of product solids.

Key to symbols:

	v,m/s	r	T_b, °C	coal
△	2.3	0.0	936	washed
●	1.1	0.93	933	washed
▲	1.4	0.0	896	washed
□	2.5	0.0	933	unwashed
○	2.0	0.56	936	unwashed
■	1.7	0.0	924	unwashed

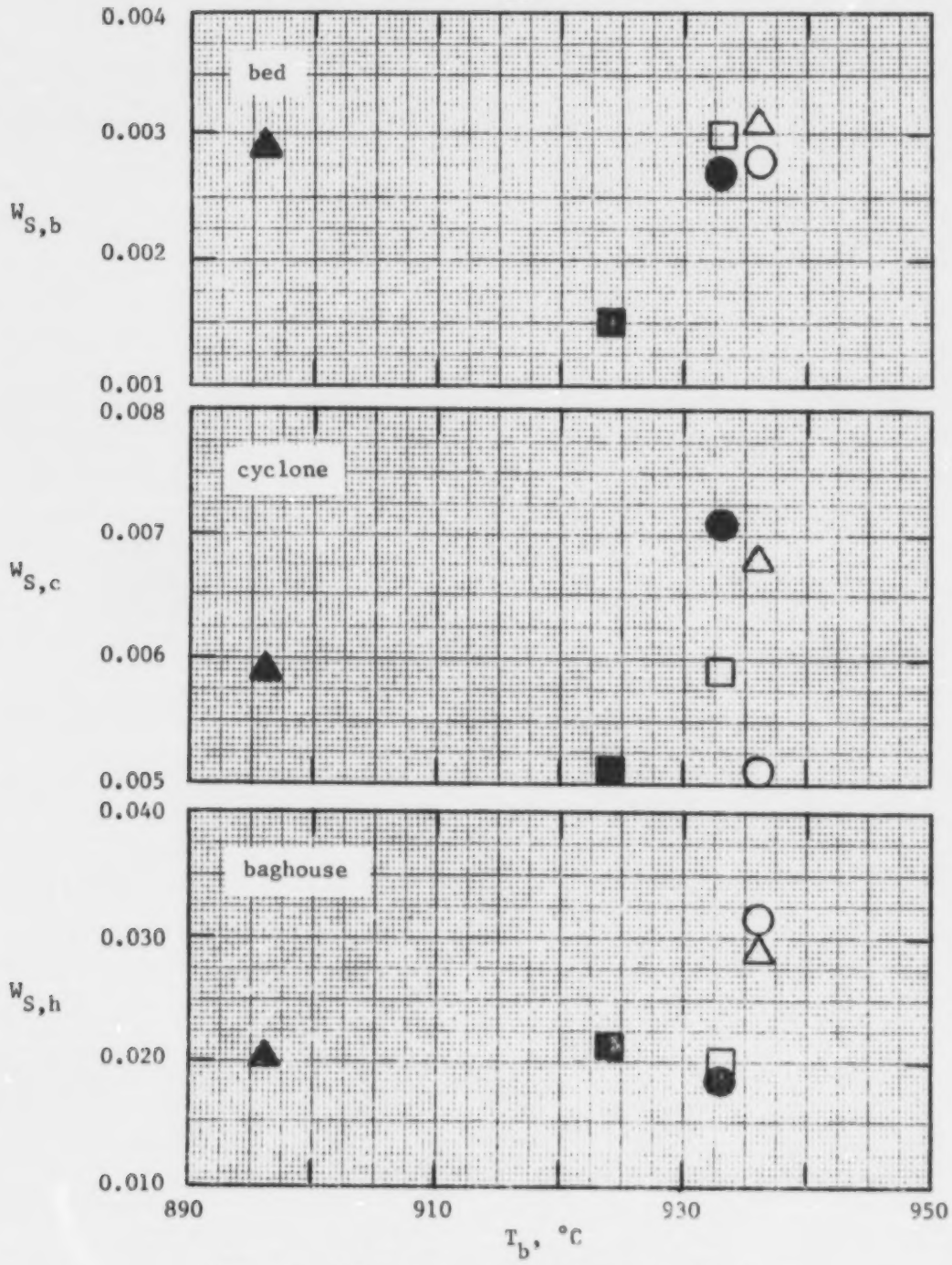


Fig. 6.2 Sulphur content of product solids.

Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

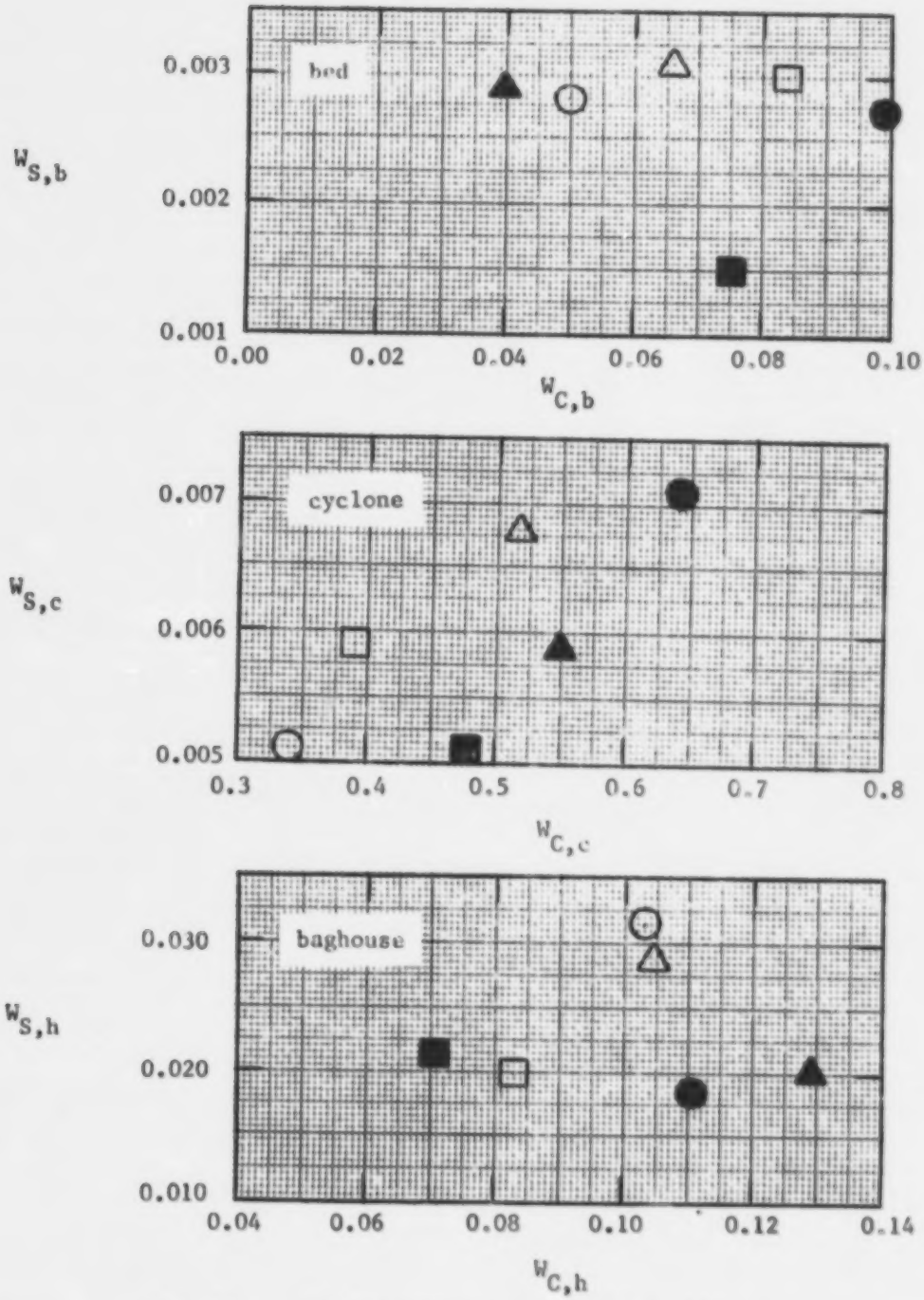


Fig. 6.3. Sulphur content of product solids.

Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

bed and baghouse solids but the sulphur content of the cyclone solids increases with carbon content. The sulphur is reported as total sulphur. No distinction is made between inorganic and organic sulphur.

6.3 Ratios of sulphur fluxes

The distribution of residual sulphur among the three streams of product solids is examined in Fig. 6.4. For the trials with no recycle of cyclone solids, approximately 66 % of the residual sulphur is carried by the cyclone solids. Each of the other two streams of product solids carry 16---18 % of the residual sulphur. Flux ratios of the residual sulphur in each of the three streams of product solids to the sulphur in the fuel are shown in Fig. 6.5. For the trials with no recycle of cyclone solids, 1---9 % of the fuel sulphur leaves as residual sulphur in the bed solids, 17---31 % in the cyclone solids and 4---9 % in the baghouse solids. At a recycle fraction of 0.93, the fraction of the fuel sulphur which leaves in the cyclone solids is reduced to 0.06 without a concomitant increase in the fraction of fuel sulphur in the streams of bed solids and baghouse solids.

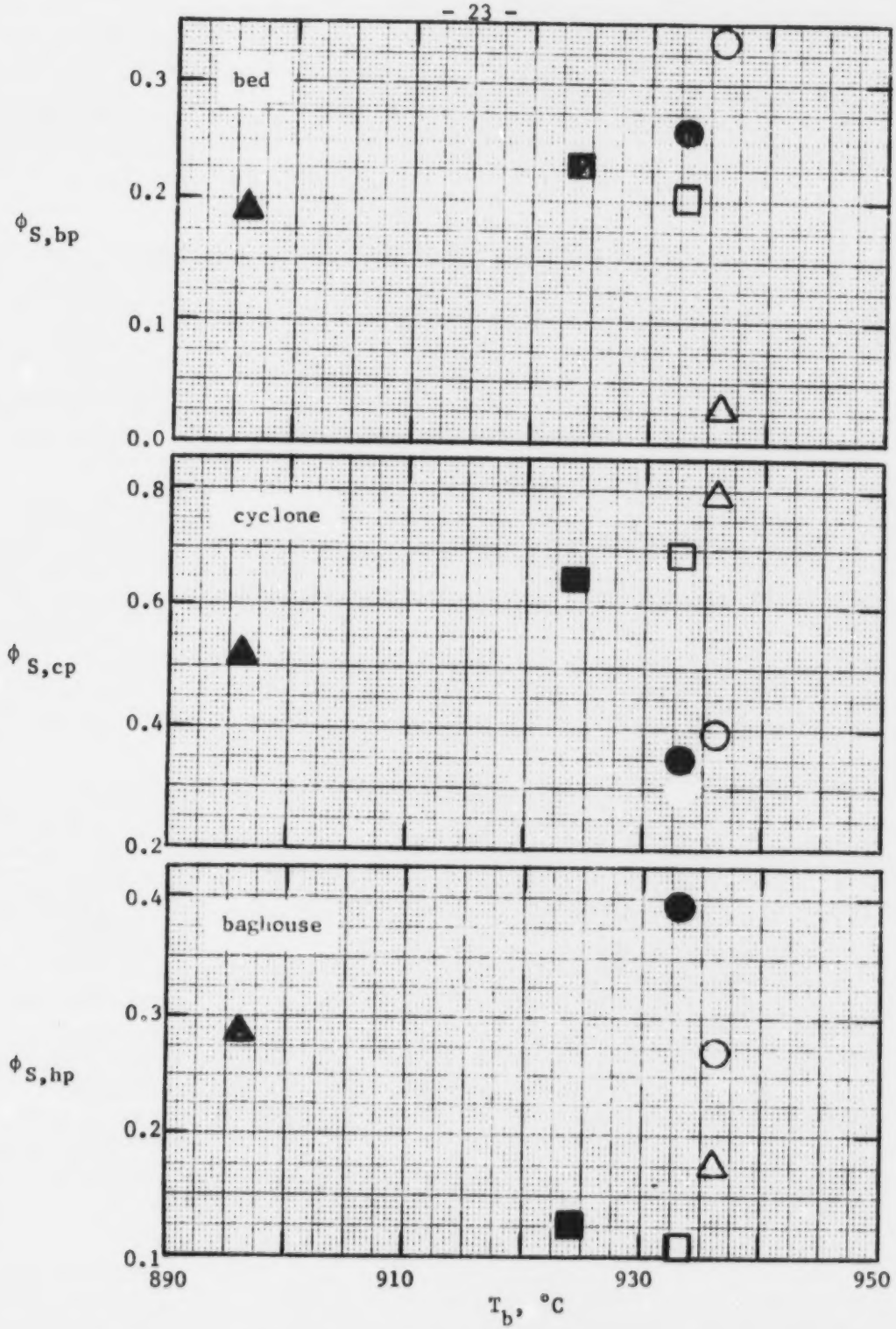


Fig. 6.4 Distribution of residual sulphur among product solids.

Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

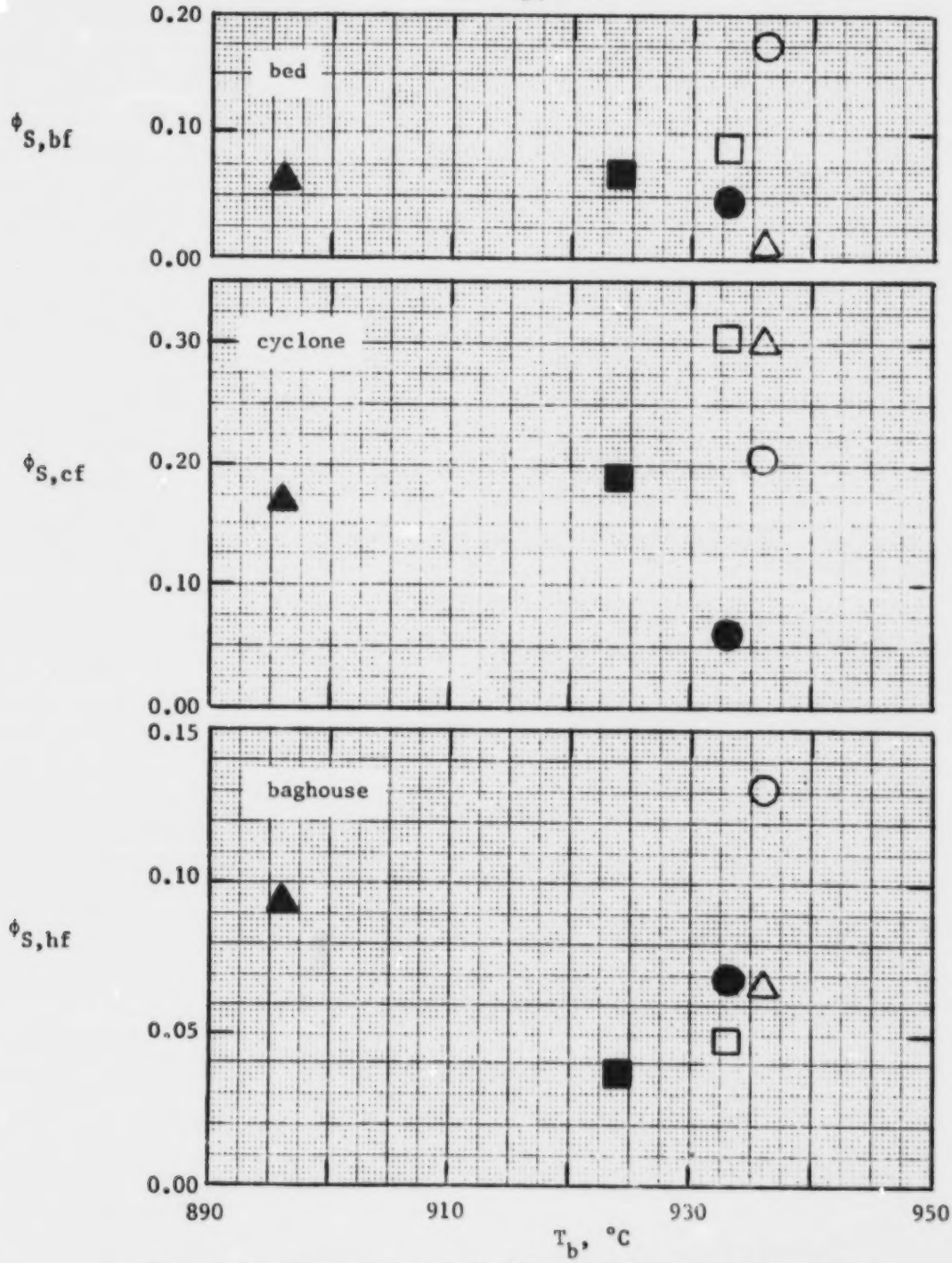


Fig. 6.5. Flux ratio of residual sulphur to fuel sulphur.

Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

7. The nitrogen balance

7.1 NO_x levels in stack gas

The NO_x levels in the stack gas on a dry basis are shown in Fig. 7.1 and Fig. 7.2. The emission levels are in the range 122---375 ppm NO_x. These values fall within the 100---400 ppm range observed in the earlier work on Devco, Evans, and Kentucky No. 9 coals (Becker et al, 1985). In the 890---940 °C range, bed temperature has no effect on the NO_x emission levels. However, there is a marked increase in the emission levels with an increase in the free oxygen concentration in the stack gas. This result agrees with the general observation that NO_x emissions are minimized by maintaining a low level of O_2 in the stack gas.

7.2 Conversion of fuel N to NO_x

The molar flux ratio, $\dot{n}_{NO_x,g}/\dot{n}_{N,f}$, or the fractional conversion of fuel N to NO_x, is examined in Fig. 7.3 and Fig. 7.4. In the calculation of this ratio the fuel is considered to be the source of nitrogen. At the operating temperature in fluidized-bed combustors, only a negligible amount of NO_x can be attributed to the oxidation of atmospheric nitrogen. As expected, the effects of bed temperature and free oxygen in the stack gas on the conversion of fuel N to NO_x parallel the observations on NO_x emissions. The fractional conversions of

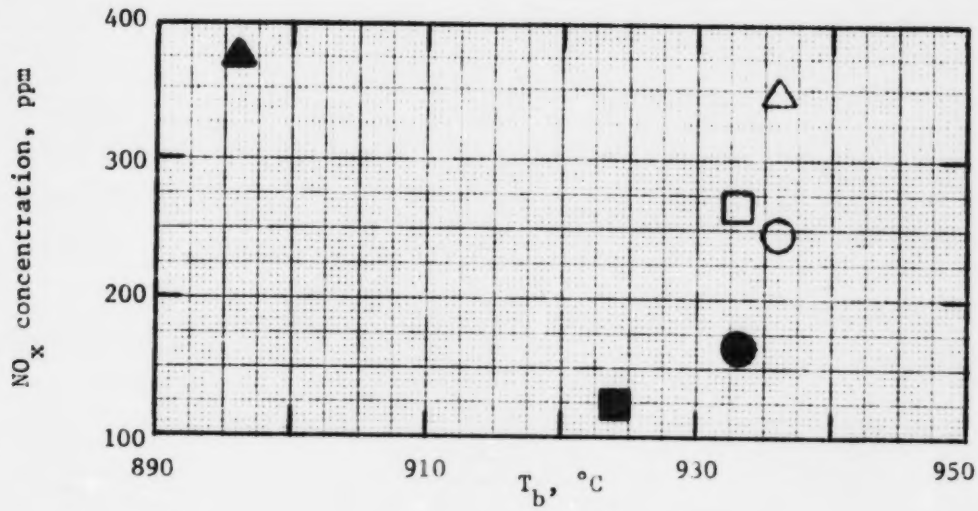


Fig. 7.1 NO_x levels in the stack gas from the fluidized bed combustion of Mt. Klappan coal.

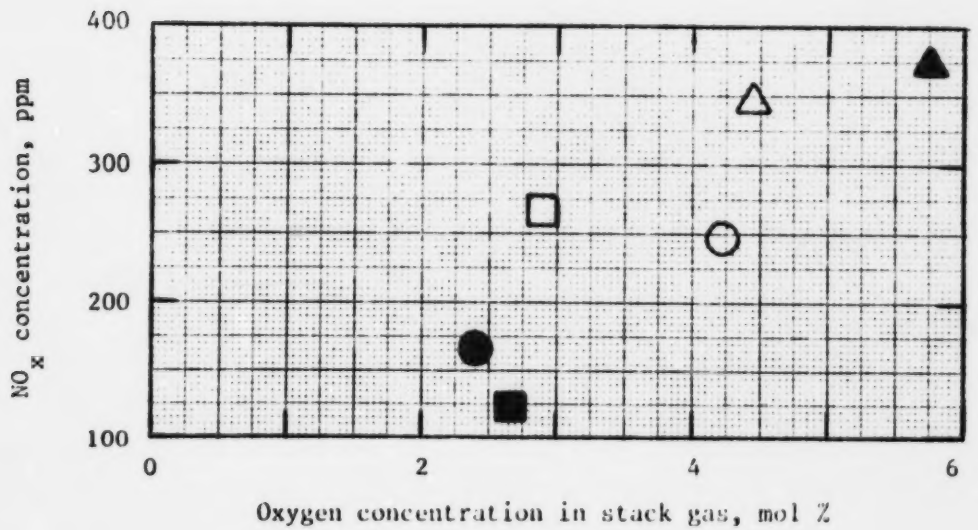
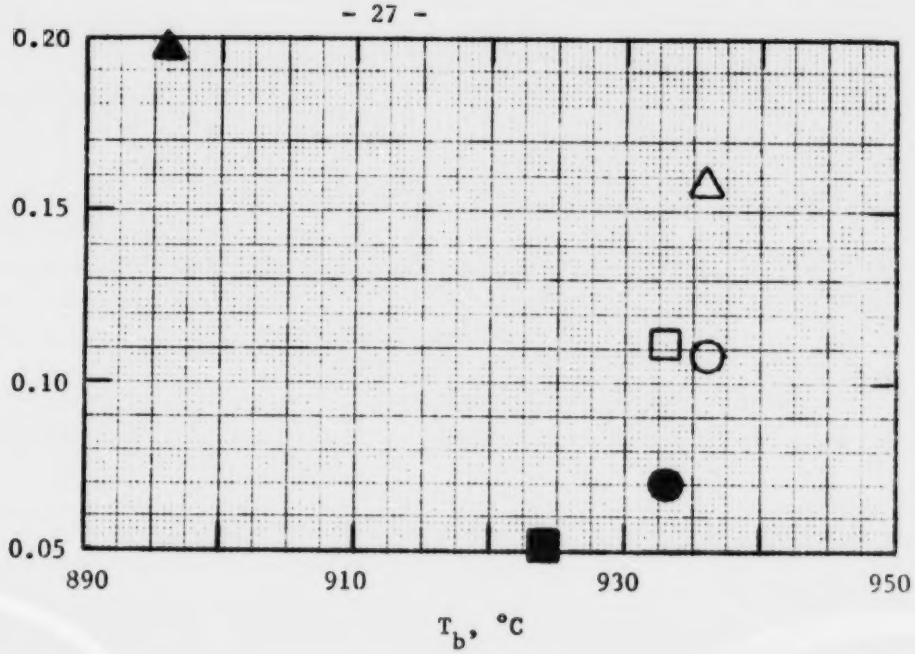


Fig. 7.2 The effect of free oxygen concentration in the stack gas on the NO_x emission levels.

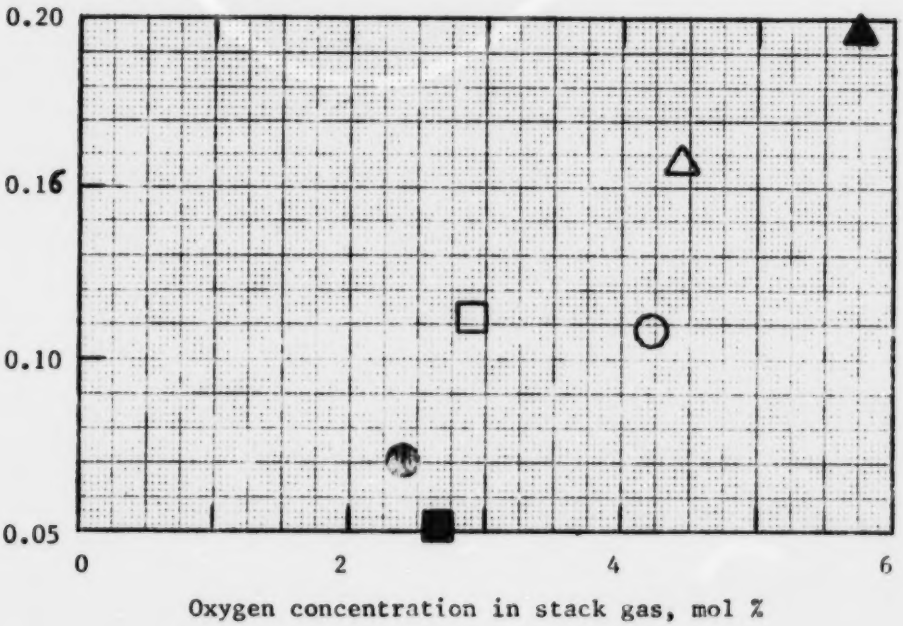
Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed



$\frac{\dot{n}_{NO_x,g}}{\dot{n}_{N,f}}$

Fig. 7.3 Fractional conversion of fuel N to NO_x.



$\frac{\dot{n}_{NO_x,g}}{\dot{n}_{N,f}}$

Fig. 7.4 The effect of oxygen level in the stack gas on the conversion of fuel N to NO_x.

Key to symbols:

	v, m/s	r	coal		v, m/s	r	coal
△	2.3	0.0	washed	□	2.5	0.0	unwashed
●	1.1	0.93	washed	○	2.0	0.56	unwashed
▲	1.4	0.0	washed	■	1.7	0.0	unwashed

fuel N to NO_x range from 0.052 to 0.196. These values fall within the range (0.05---0.2) observed in the combustion studies on Devco, Evans and Kentucky No. 9 coals (Becker et al, 1985).

8. Comparison with Highvale coal

8.1 Carbon burn-up efficiencies

Carbon burn-up efficiencies for Mt. Klappan and Highvale coals are plotted versus the concentration of free oxygen in the stack gas in Fig. 8.1. Highvale coal, a reactive, low-sulphur, sub-bituminous coal from Alberta, is one of the candidate fuels examined in this current series of combustion studies. The superior burning characteristics of Highvale coal is clearly evident from this plot. For conditions of zero recycle of cyclone solids, carbon burn-up efficiencies of 98.1 to 99.7% were obtained with Highvale coal while the efficiencies with Mt. Klappan coal were limited to the 78.0---86.6 % range. A recycle fraction of 0.93 was required to achieve a burn-up efficiency of 94.2 % with Mt. Klappan coal.

Lim et al (1984) have examined the combustion of a number of solid fuels, including Mt. Klappan coal, in a spouted bed combustor. The low reactivity of Mt. Klappan coal required the initial burning of a more reactive coal to bring the bed temperature to 900 °C for the initiation of combustion. For the two successful runs with Mt. Klappan anthracite they report

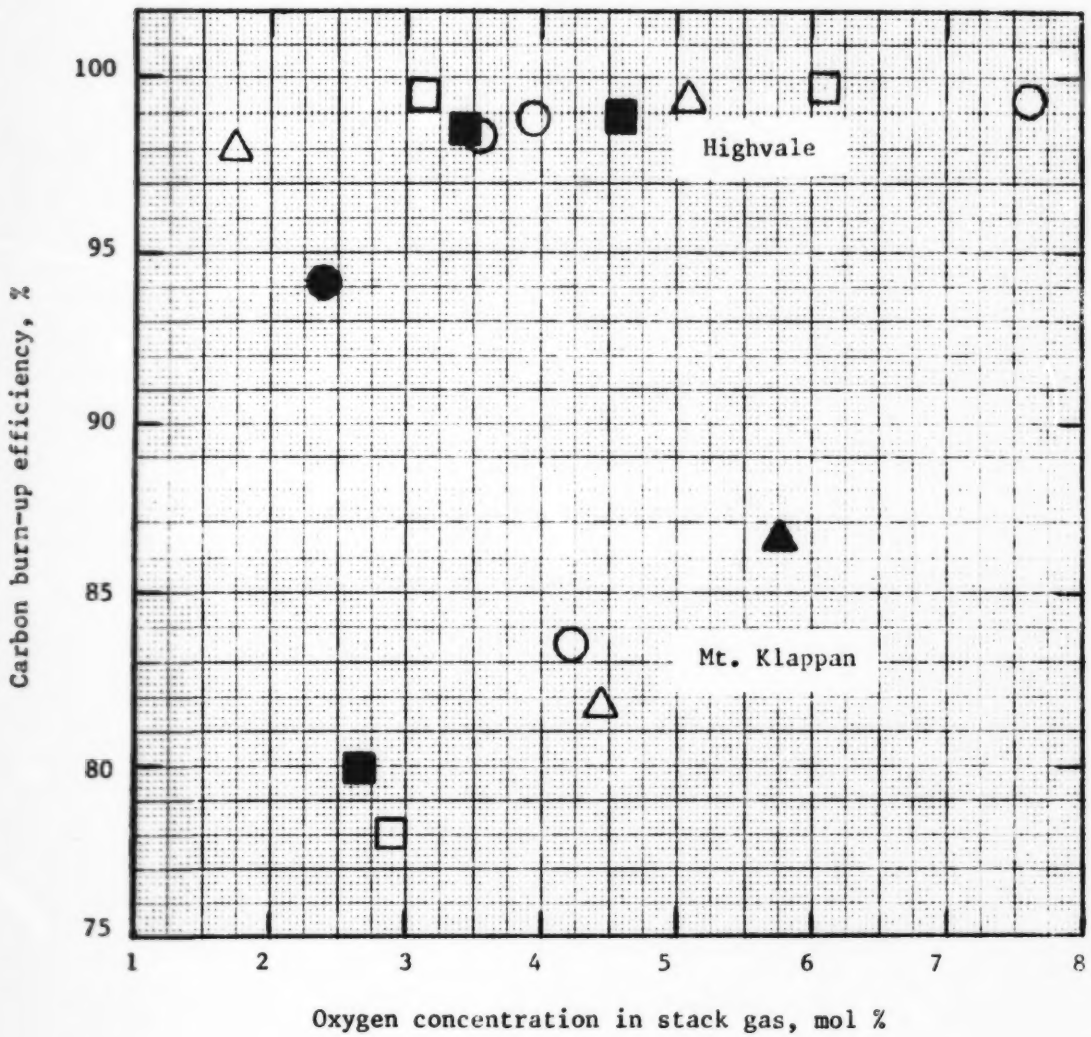


Fig. 8.1 Comparison of carbon burn-up efficiencies for Mt. Klappan and Highvale coals.

Key to symbols:

Mt. Klappan

	v, m/s	r	T_b, °C		v, m/s	r	T_b, °C
△	2.3	0.0	936	□	2.5	0.0	933
●	1.1	0.93	933	○	2.0	0.56	936
▲	1.4	0.0	896	■	1.7	0.0	924

Highvale

△	1.4-1.5	0.0	847-851	□	1.2-1.5	0.0	950-952
○	2.2-2.4	0.0	847-851	■	2.7-3.1	0.0	951-954

combustion efficiencies of 80.7 and 87.0 %. These runs were carried out at bed temperatures of 870---914 °C and excess air levels of 70---90 %.

9. Conclusion

A brief summary of the principal findings on the fluidized-bed combustion of Mt. Klappan anthracite follows.

Mt. Klappan coal is a refactory fuel. A high recycle of elutriated fines is required to achieve an acceptable level of combustion efficiency. Without recycle of cyclone solids, overhead carbon losses can amount to as much as 20 % of the carbon in the fuel.

Closures on the sulphur balances are unsatisfactory. Estimates of the residual sulphur in the product solids based on the flowrates and analyses of the stack gas range from 43.4 to 90.1 % of the fuel sulphur compared to estimates of 17.4 to 52.3 % based on the flowrates and analyses of the product solids. There is no apparent effect of carbon content on the levels of residual sulphur in the bed and baghouse solids but the sulphur content of the cyclone solids increases with carbon content. With no recycle of cyclone solids, approximately 66 % of the residual sulphur is carried by the cyclone solids. Each of the other two streams of product solids carry 16---18 % of the residual sulphur. The fraction of the fuel sulphur leaving in

the cyclone solids is in the 0.2---0.3 range. At a recycle fraction of 0.93, this fraction is reduced to 0.06.

$N\Theta_x$ emission levels in the stack gas on a dry basis are in the same 100---400 ppm range observed in the earlier work on Devco, Evans and Kentucky No. 9 coals. The marked increase in NO_x emissions with an increase in free oxygen concentration in the stack gas agrees with the general observation that NO_x emissions are minimized by maintaining a low level of O_2 in the stack gas. The fractional conversion of fuel N to NO_x also falls within the 0.05---0.2 range observed in the combustion studies on Devco, Evans and Kentucky No. 9 coals.

References

Anthony, E.J., 1985, private communication, Energy Research Laboratories, Energy Mines and Resources Canada, CANMET, Ottawa

Becker, H.A. and Code, R.K., 1982, The Pilot Plant Installation at Queen's University for Studies of Atmospheric Fluidized Bed Combustion. Report QFBC.TR.82.1, Queen's Fluidized Bed Combustion Laboratory, Department of Chemical Engineering, Queen's University, Kingston, Canada K7L 3N6

Becker, H.A. and Code, R.K., 1983, Pilot Plant Trials on Atmospheric Fluidized Bed Combustion of High-Sulphur Eastern Canadian Coals (Minto and Devco) with Limestone Addition for Sulphur Capture. Report to Energy Mines and Resources Canada, CANMET, Ottawa. Report QFBC.TR.83.1, Queen's Fluidized Bed Combustion Laboratory, Department of Chemical Engineering, Queen's University, Kingston, Canada K7L 3N6

Becker, H.A., Code, R.K., McCleave, R.W. and Stephenson, J.R., 1985, Pilot Plant Studies of Fluidized Coal Combustion. Report to Energy Mines and Resources Canada, CANMET, Ottawa. Report QFBC.TR.85.1, Queen's Fluidized Bed Combustion Laboratory, Department of Chemical Engineering, Queen's University, Kingston, Canada K7L 3N6

Lim, C.J., Barua, S.K., Epstein, N., Grace, J.R. and Watkinson, A.P., 1984, Spouted Bed and Spout-Fluid Bed Combustion of Solid Fuels, Institute of Energy, London, October 16-17